

BAPBA 1379/1



Marine Geology 162 (2000) 225–236

**MARINE
GEOLOGY**

 INTERNATIONAL JOURNAL OF MARINE
GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS

www.elsevier.nl/locate/margeo

N° 2-4

Origin of the New Caledonian ophiolites based on a French–Australian Seismic Transect

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Received 29 October 1998; accepted 21 June 1999

Abstract

The origin, age and nature of the New Caledonian ophiolites are still debated. Recently, as part of the joint French–Australian Seismic Transect (FAUST) program, the Australian research vessel *Rig-Seismic* recorded a series of multichannel deep-seismic profiles between the New Hebrides Arc and the Australian margin. These profiles, which ran south of New Caledonia, image the southern prolongation of the overthrust ophiolites and allow a new interpretation of the Eocene compressive tectonism along the New Caledonia–Norfolk Ridge. A model involving abduction of the whole oceanic lithosphere of the Loyalty Basin is consistent with the age and origin of the ophiolite. Variations in tectonic style along strike in the north–south-trending part of the Norfolk Ridge have produced ophiolite exposures related to uplifted and partially overthrust upper mantle slivers within the southern part of the Loyalty Basin. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: ophiolites; abduction; seismic profiling; New Caledonia; Southwest Pacific; Loyalty Basin

1. Introduction

New Caledonia (Fig. 1) is located on the Norfolk Ridge which is one of the major features between the New Hebrides Arc and the eastern Australia margin. The geological framework of the area is related to

successive opening of subparallel oceanic basins since the late Cretaceous. This divergence involved the opening of the Tasman Sea. New Caledonia and Loyalty Basins (Weissel and Hayes, 1977; Mignot, 1984; Symonds et al., 1996; Van de Beuque et al., 1998a,b), and isolated two main elongate continental fragments: the Lord Howe Rise, between the Tasman Sea and the New Caledonia Basin, and the Norfolk Ridge, east of the New Caledonia Basin.

During the late Eocene, a slab of oceanic lithosphere was thrust over the island of New Caledonia

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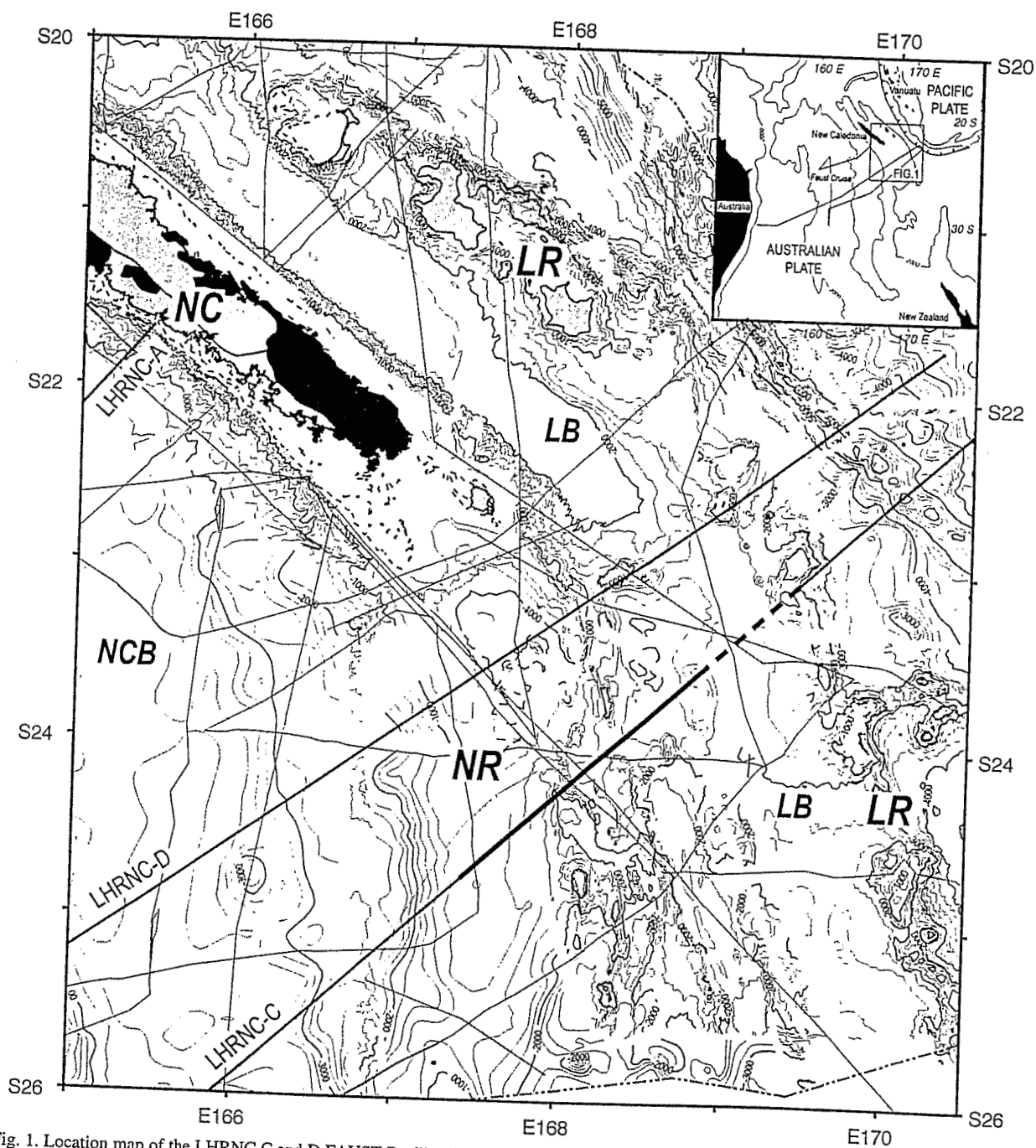


Fig. 1. Location map of the LHRNC C and D FAUST Profiles, in heavy lines. The location of sections shown on Figs. 3 and 4 are indicated as dotted line (Fig. 3) and continuous heavy line (Fig. 4). The thin lines indicate the oil companies deep seismic profiles shot in the area. NC: New Caledonia; LB: Loyalty Basin; LR: Loyalty Ridge; NR: Norfolk Ridge; NCB: New Caledonian Basin. The insert shows the location of New Caledonia within the SW Pacific Region.

from N–NE to S–SW (Avias, 1967; Paris, 1981). The Loyalty Basin to the east of the Norfolk Ridge is considered the key to the origin of the ophiolites. This elongate, 80-km wide basin lies at depths of 1900–3800 m, and is bound to the northeast by the volcanic Loyalty Islands.

The origin of the New Caledonian ophiolites has been debated for more than 30 years (Avias, 1967; Paris, 1981), and several models have been proposed. The Middle to Late Eocene age of the obduction of the ophiolites, in response to roughly north–south shortening between the Pacific and Australian Plates (DeMets et al., 1994), is the only point on which most models agree. However, the age of Loyalty Basin, and the geometry of the subduction and obduction, remain controversial.

Kroenke and Rodda (1984) interpreted New Caledonia as a continental fragment that separated from Lord Howe Rise during Late Cretaceous to Paleocene opening of the New Caledonian Basin. They proposed that the oceanic basement of the New Caledonia Basin was subducted beneath the western margin of New Caledonia during the Eocene resulting in the opening of the Loyalty Basin in a backarc setting. The newly formed lithosphere of the Loyalty Basin immediately underwent compression and was obducted over the New Caledonia Ridge during the Late Eocene.

Collot et al. (1987) used geophysical and radiochronological data (Prinzhofer, 1981) to support a model in which the Loyalty Basin formed as a marginal basin prior to the Late Cretaceous (~80

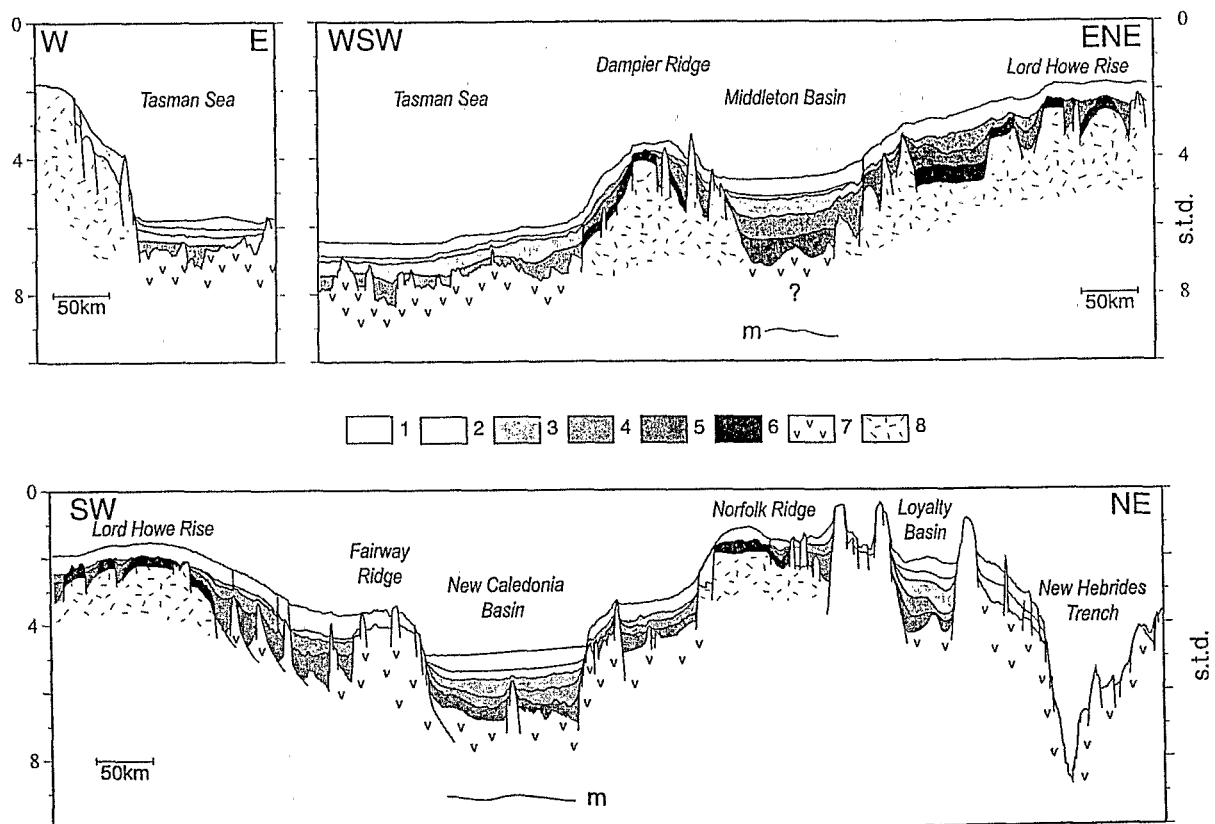


Fig. 2. Synthetic profile resulting from the interpretation of FAUST survey. (1) Late Oligocene to Present-day sediments, (2) Late Eocene to Late Oligocene sediments, (3) Late Paleocene to Late Eocene sediments, (4) Late Cretaceous to Late Paleocene, (5) Lower to Late Cretaceous sediments, (6) Antecretaceous sediments, (7) Oceanic or intermediate basement, (8) Continental basement, *m* = Mohorovicic discontinuity. Vertical exaggeration = 40.

Ma), with Late Cretaceous to Early Paleocene subduction occurring to the west of New Caledonia. Up until the end of the Late Eocene, shortening between the Australia and Pacific Plates was absorbed along this subduction zone, leading to southeasterly obduction of Loyalty Basin crust over New Caledonia.

In another model proposed by Régnier (1988), the Late Eocene compressive phase affected both the eastern and western margins of the New Caledonia–Norfolk Ridge system, with subduction of New Caledonia Basin crust occurring along the western margin. In this model, the exact temporal relationship between the subduction and the Late Eocene obduction of the New Caledonian ophiolites remains unresolved.

In April 1998, a series of deep-seismic profiles were recorded between New Caledonia and Australia by the Australian Geological Survey Organisation (AGSO) using its vessel RV *Rig-Seismic* for a French–Australian collaborative study (FAUST) (Fig. 1). Two of these profiles, LHRNC-C and D, provide evidence for the origin of New Caledonian

ophiolites and the tectonic evolution of the area. In this article profile LHRNC-C is used to illustrate the geology of the area — profile LHRNC-D, which lies about 80 km to the north, images very similar features.

2. Results of the FAUST survey

2.1. Depositional history of basins to the west of New Caledonia

The FAUST survey (Fig. 1) utilised a dual array with a total of 20 airguns (about 3000 cubic-inches in volume), that allowed deep penetration of the sedimentary cover, up to and beyond basement on 4500 km of long profiles (Lafay et al., 1998; Van de Beuque et al., 1998a,b; Bernardel et al., 1999).

The new FAUST profiles, together with a reinterpretation of all existing seismic profiles in the area

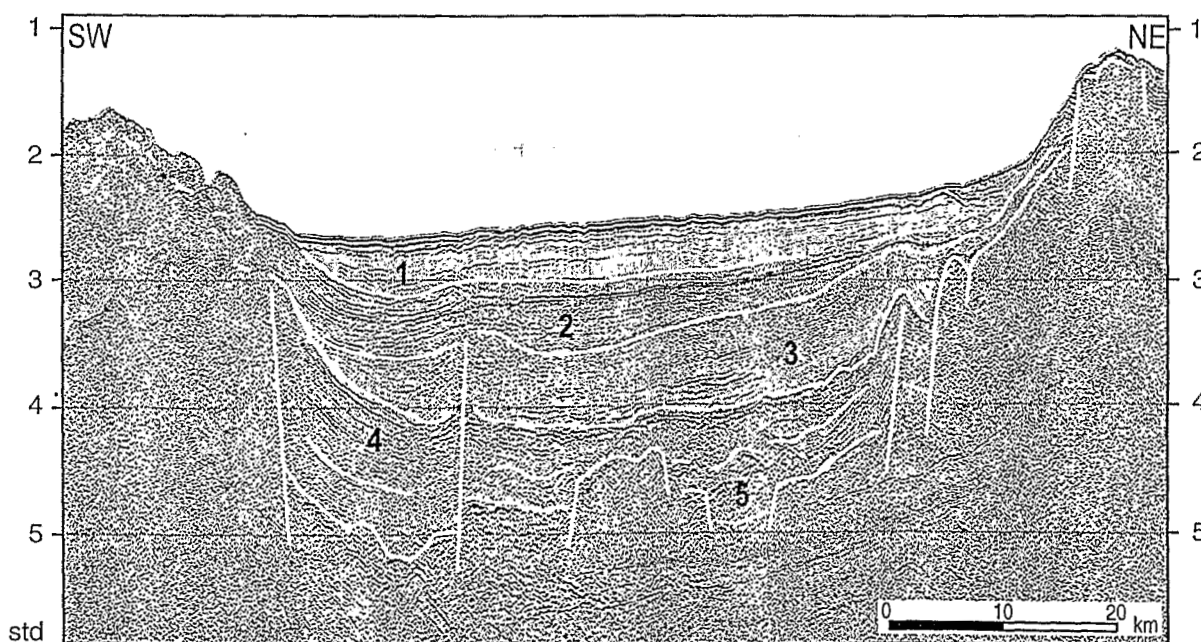


Fig. 3. Northeastern part of LHRNC-C profile: (1) Late Oligocene to present-day sediments, (2) Late Eocene to Late Oligocene sediments, (3) Late Paleocene to Late Eocene sediments, (4) Late Cretaceous to Late Paleocene, (5) Lower to Late Cretaceous sediments. Vertical exaggeration = 15.

ties to DSDP 206, 208 (Burns et al., 1973) and 286 (Andrews et al., 1975), provide a new understanding of the depositional history of the basins to the west (Tasman Sea, Middleton Basin, New Caledonia Basin) and east (Loyalty Basin) of New Caledonia (Fig. 2).

The opening of the Tasman Basin occurred between chrons 33 and 24 (82 and 54 Ma) (Weissel and Hayes, 1977; Weissel et al., 1977; Gaina et al., 1998) from the Late Cretaceous to Paleocene. Based

on results from DSDP 206 and 208 and the revised seismic interpretation, the Middleton and New Caledonia Basins are thought to be equivalent in age or slightly older (Lower Cretaceous, Uruski and Wood, 1991) than the Tasman Basin. The sediment fill within these basins has been described by Ravenne et al. (1977), Symonds and Willcox (1989) and more recently by Van de Beuque et al. (1998a; b). Four main depositional episodes have been defined from conventional seismic data: 1 — Early Oligocene to

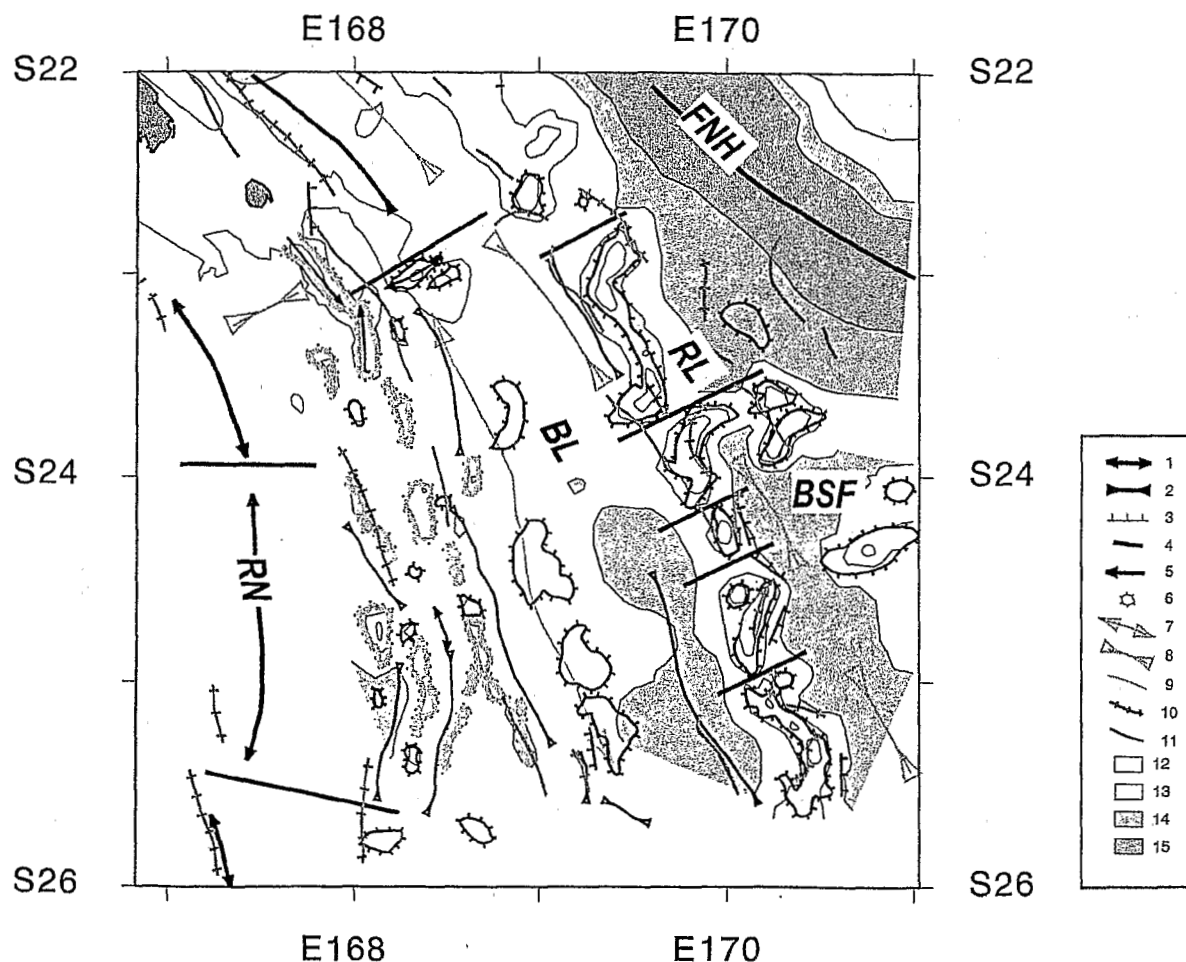


Fig. 4. Structural Sketch of the southern part of Norfolk Ridge with the magnetic lineations, the gravity anomalies and structural features deduced from bathymetry and seismic interpretation (after Van de Beuque, 1999). (1, 2, 3 and 4) Ridges, depressions, normal faults and strike-slip fault deduced from bathymetry, (5) canyon, (6) seamounts, (7, 8 and 9) Ridges, depressions and faults of the basement deduced from seismic data, (10 and 11) Positive and negative magnetic anomalies, (12) Gravity anomaly above +100 mGal, (13) Gravity anomaly comprised between +30 and +100 mGal, (14) Gravity anomaly comprised between -30 and -100 mGal, (15) Gravity anomaly lower than -100 mGal. The positive gravity anomalies corresponding to the basement slivers are in blue.

the present-day; 2 — a Late Paleocene to Middle Eocene episode with its top reflecting a Late Eocene erosional phase on the ridges related to compressive deformation throughout the area; 3 — a Late Cretaceous to Paleocene episode associated with the main phase of seafloor spreading; 4 — a Middle Cretaceous synrift episode.

On the FAUST seismic profiles, the sedimentary thickness in the Tasman Sea averages about 1.5 s (two-way time — TWT), in the Middleton basin and about 2 s (TWT) in the New Caledonia Basins (Fig. 2). In Middleton and New Caledonia Basins, five sequences (5 to 1) have been distinguished and interpreted by tying the new and existing seismic data (Van de Beuque, 1999) to DSDP 208 (Burns et al., 1973). The oldest sedimentary rocks sampled at DSDP 208 hole were Late Cretaceous in age and still way above seismic basement. Therefore, it seems reasonable to interpret the lowest sedimentary sequence overlying basement as older than Late Cretaceous. Sequence 5 overlies seismic basement within the basins and is bounded at its top by a strong reflector. It is about 0.4 s thick within the basins and is thought to consist of an Early to Late Cretaceous sequence deposited in response to Early Cretaceous rifting throughout the area (Ravenne et al., 1977). Sequence 4 either overlies sequence 5, or in some places, mainly on the ridges, directly overlies basement. Its thickness varies from 0.5 s in the Middleton Basin to a maximum of 0.6 s in the New Caledonia Basin. This sequence has been partly sampled by DSDP hole 208, where it comprises a Maastriachian to Late Paleocene section. Sequence 4 is therefore interpreted as being Late Cretaceous to Late Paleocene section. Sequence 3, also sampled by DSDP 208 is extremely variable in thickness due to the uplift and erosion of the crests of high-standing features (Lord Howe Rise and Fairway Ridge) as a result of Middle to Late Eocene compressive events (Avias, 1967; Paris, 1981). In the basins, the sequence 3 is more consistent in thickness and includes Late Paleocene to Late Eocene section. Sequences 2 and 1 are more continuous throughout the area and constitute the post-tectonic cover. The DSDP results and seismic correlation indicate that sequence 2 was deposited from the Late Eocene to Late Oligocene and sequence 1 from the Late Oligocene to the present-day.

2.2. Depositional history of the Loyalty Basin

Due to a lack of penetration on existing seismic data in the Loyalty Basin, only the upper two sequences were interpreted. This incomplete understanding of the depositional history led Bitoun and Récy (1982) to suggest an Eocene age for the formation of the Loyalty Basin.

The improved quality of the FAUST seismic profiles allows a much more precise understanding of basin fill, particularly on its eastern margin. Profile LHRNC-C (Fig. 3) indicates that below the base of sequence 2, which was interpreted as Eocene in age, there is a further 1.5 to 2 s of sediment. In addition, seismic correlation from west of New Caledonia region to the Loyalty Basin shows a close similarity between the five sequences of the New Caledonia Basin and those identified within this part of the Loyalty Basin. The similar seismic characteristics and thicknesses of the five sequences in both basins imply that the Loyalty Basin is considerably older than the suggested Eocene age (Bitoun and Récy, 1982; Kroenke and Rodda, 1984). That is, it may have formed in the Early Cretaceous at the same time as the New Caledonia and Middleton Basins (Ravenne et al., 1977). An Eocene age for the creation of the Loyalty Basin requires a very high sedimentation rate to deposit the 2.5 s of section within the basin. This rate would have been about twice than for the New Caledonia and Middleton Basins, and is difficult to explain.

Further evidence for an older age for the formation of the Loyalty basin is provided by the dating of the New Caledonia ophiolites themselves. If the ophiolites were once part of the Loyalty Basin basement, then their radiometric K/Ar dating confirms a Cretaceous age (120 Ma; Prinzhofer, 1981) for the basin.

2.3. Structure of the Loyalty Basin

The Loyalty Basin, lying northeast of the New Caledonia mainland, is an elongate flat-floored basin, about 80 km wide. Its depth varies from southeast to northwest between 2000 and 3500 m. The basin is bounded in the northeast by the volcanic Loyalty

Ridge, which is composed of two phases of alkaline basalts and dolerites dated by the K/Ar method at 29 and 9–11 Ma (Chevalier, 1968; Baubron et al., 1976; Monzier, 1993).

South of New Caledonia, the structure of the Loyalty Basin becomes much more complicated because of the occurrence of a series of elongated ridges trending N 170°, and isolated seamounts (Fig. 4). The elongated ridges rise to less than 1000 m depth, and some are pierced by steep volcanoes that shallow to less than 500 m. The ridges correspond to large gravity highs without significant magnetic signature, whereas the volcanoes are associated with strong positive magnetic anomalies (Fig. 4). In this area, the overall width of this complex system is about 200 km.

Seismic profile LHRNC-C (Fig. 5) is a south-west–northeast section across the southwestern part of the Loyalty Basin. At the northeastern end of the profile, which corresponds to part of the detailed seismic image shown in Fig. 3, the Loyalty Basin contains a thick sedimentary section consisting of the five sequences described above. At the southwestern end of the profile, the Norfolk Ridge, which is the southern extension of New Caledonia, is a basement ridge overlain by an incomplete sedimentary section consisting of sequences 1 and 2 overlying an older succession containing erosional surfaces.

The middle of the profile images a succession of basement slivers, some outcropping and some covered by a thin sedimentary section consisting only of post-Eocene sequences 1 and 2. In the east near the edge of the Loyalty Basin, uplifting of the basement slivers has resulted in deformation of the sedimentary section to the top of sequence 2 (Late Oligocene).

3. The age, nature and origin of the ophiolites

The ophiolitic nappe on the New Caledonia mainland essentially occupies the southern part of the island to 21°30'S, where it consists of a continuous massif. North of this latitude, the ophiolites are displaced toward the west coast and appear as a succession of small, isolated allochthonous massifs extending up to the Belep Islands. They consist exclusively of upper mantle material (serpentinites

and harzburgites), without oceanic crust except for a very small outcrop in the southern massif (Montagne des Sources). There is general agreement for an Eocene age for the obduction of the ophiolites onto New Caledonia. However, the original age of the rocks forming the ophiolites is still controversial, and depends on the age and origin of the Loyalty Basin. Bitoun and Récy (1982) proposed an Eocene age for the Loyalty Basin, whereas Prinzhofer (1981), Collot et al. (1987), Cluzel et al. (1994; 1997) and Eissen et al. (1998) suggested ages varying from Early to Late Cretaceous, respectively.

The origin of the ophiolites is also debated. Dubois et al. (1974), Kroenke and Rodda (1984) and Collot et al. (1987) suggested that the obduction of the ophiolites resulted from the eastward subduction of New Caledonia Basin basement under the New Caledonia mainland. However, Aubouin et al. (1977), Cluzel et al. (1994; 1997), Aitchison (1995), Cluzel (1998), related the obduction to the southward subduction of the Loyalty Basin. The first hypothesis implies a diachronic process for the obduction mechanism (Cluzel et al., 1997). Initially, the allochthonous basalts outcropping on the west coast of the New Caledonia were emplaced, and may have originated as a volcanic plateau within the Loyalty Basin. This was followed by overthrusting of the peridotites that originated from a section of lithosphere located north of the New Caledonia mainland. In the second hypothesis, the obducted basement is exclusively upper mantle material (Paris, 1981), and the west coast basalts are seen as being completely allochthonous.

The interpretations of the seismic data to the south of New Caledonia, as described previously, support the following evolutionary model.

(1) The basement of the Loyalty Basin is older than Eocene, probably Early to Late Cretaceous, as inferred by the thickness of its sedimentary section, and the existence of the five sequences recognised in the New Caledonia and Middleton Basins, which are thought to have formed in the Cretaceous. This interpretation is strongly supported by the only dating of the ophiolite material, which gave a Cretaceous age (120 Ma; Prinzhofer, 1981).

(2) The area south of New Caledonia imaged by the FAUST profiles constitutes the lateral southward prolongation of the ophiolites obducted on New

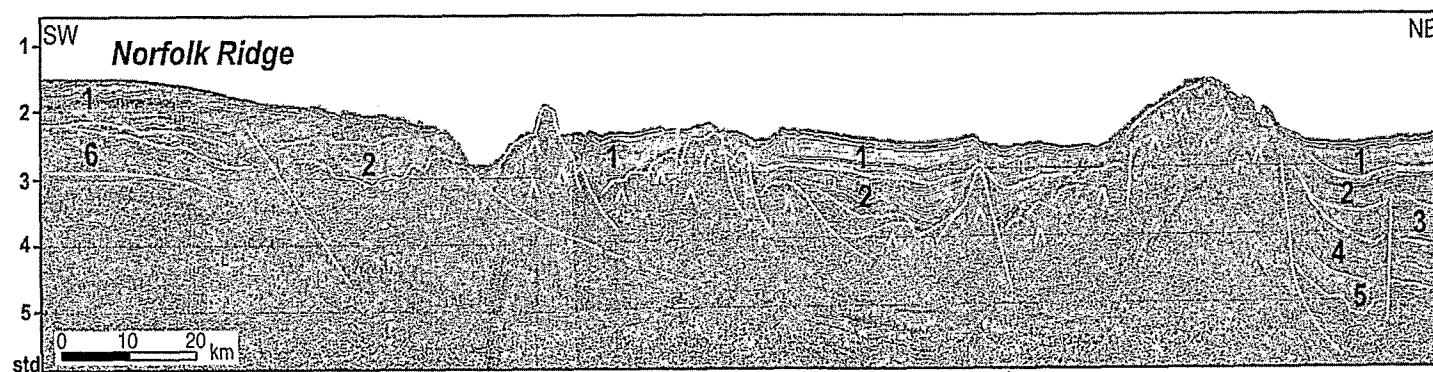


Fig. 5. Southwestern part of LHRNC-C profile. The Southwestern part of the profile cuts the Norfolk Ridge south of New Caledonia. In the central and northeastern part of the profile, three main basement slivers are covered by a reduced sedimentary sequence; (1) Late Oligocene to present-day sediments, (2) Late Eocene to Late Oligocene sediments, (3) Late Paleocene to Late Eocene sediments, (4) Late Cretaceous to Late Paleocene, (5) Lower to Late Cretaceous sediments, (6) Sedimentary cover on the Norfolk ridge basement. The age of this sequence is probably older than Cretaceous and represents the initial coverage of the area (Devonian, Carboniferous,...). Vertical exaggeration = 14.

Caledonia. The geophysical data indicates that the elongated basement massifs in this area, are mainly mantle material. That is, they are associated with large gravity highs but lack the magnetic anomalies that would indicate the presence of oceanic crust.

(3) The fact that this part of the Loyalty Basin has not been obducted is a result of the geometry of the shortening during the Eocene. If we agree with most workers that the shortening between the Loyalty Basin and New Caledonia is roughly oriented north–south, the compressive component is a maximum in front of New Caledonia, which was oriented N 140°. In the southern segment, which was oriented N 170°, this compressive component would have produced strike-slip motion and only resulted in uplifting of basement slivers. The same phenomenon may have occurred to the north of New Caledonia where the Norfolk Ridge also has a north–south orientation.

(4) The absence of a crustal sequence above the upper mantle on land can be explained by erosion of this sequence after the obduction. It is, however, difficult to envisage the complete erosion of 5 to 6 km of crust without any trace remaining onshore. Another hypothesis (Dubois et al., 1974) relates the absence of the crustal sequence to tectonic erosion associated with gravity sliding resulting in the outcropping of the mantle material. This last hypothesis, which we support here, was suggested in part by Paris (1981). Prior to obduction, the Loyalty Basin basement was affected by an intra-oceanic tectonic episode that resulted in the denudation of the upper mantle, and the creation of upper mantle slivers

forming topographic highs, which were then obducted. Such a model has already been proposed to explain the existence of large slivers of upper mantle in an abnormal topographic position in the ocean-like Futuna Island, north of Fiji Islands (Régner, 1994), and Gorringe Bank, west of Portugal (Auzende et al., 1978).

The cartoon in Fig. 6 presents a conceptual present-day cross-section of the whole area between the New Hebrides Trench and the New Caledonia Basin. It incorporates the lateral variation between the southern New Caledonia domain, where the basement of the Loyalty Basin is now a succession of slivers, to the more northerly domain where the ophiolite nappe overthrusts the New Caledonia mainland. The proposed incipient subduction zone to the west of New Caledonia is deduced after the hypothesis of Régner (1987). The change in orientation of the Norfolk Ridge from N 140° in the north, to N 170° to the south, and its association with the overthrust ophiolites onland and the basement slivers to the south (Fig. 7), is probably not the result of the Eocene shortening event, but was inherited from an earlier stage in the evolution of the area during the Cretaceous rifting.

The present-day relatively shallow depth of the Loyalty Basin, compared with the depth of the contemporaneous, Cretaceous New Caledonia or Tasman basins, can be explained by shortening/crustal thickening during the Eocene compression. Alternatively, the peculiar position of the Loyalty Basin at the junction of the collision zone of the Australian plate with the New Hebrides Arc, could account, at

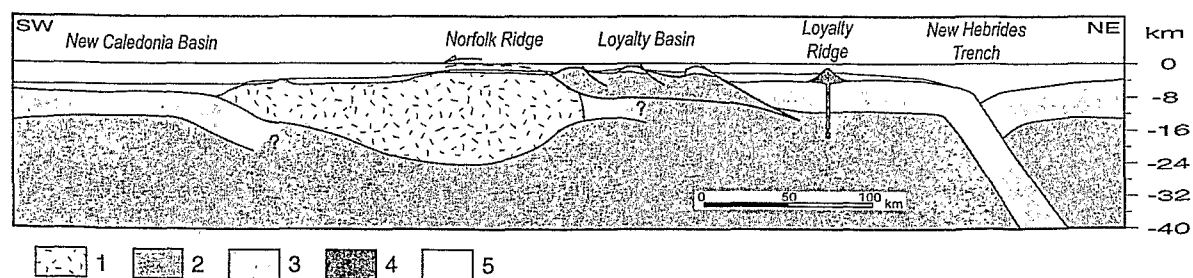


Fig. 6. Synthetic profile illustrating the origin of New Caledonian Ophiolites: (1) Continental or intermediate basement, (2) Upper mantle, (3) Oceanic crust, (4) Volcanics, (5) sedimentary cover. The subduction of the New Caledonia Basin basement under the western margin of New Caledonia is deduced from Régner (1988). This phenomenon is probably related to a shortening episode synchronous or immediately after the main Eocene phase. The location of Figs. 3 and 5 are indicated. Vertical exaggeration = 2.5.

least for part of its shallow depth, by recent uplift. This collision is also responsible for the uplift of the

Norfolk and Loyalty Ridges, and for the diffuse distribution of seismicity throughout the region.

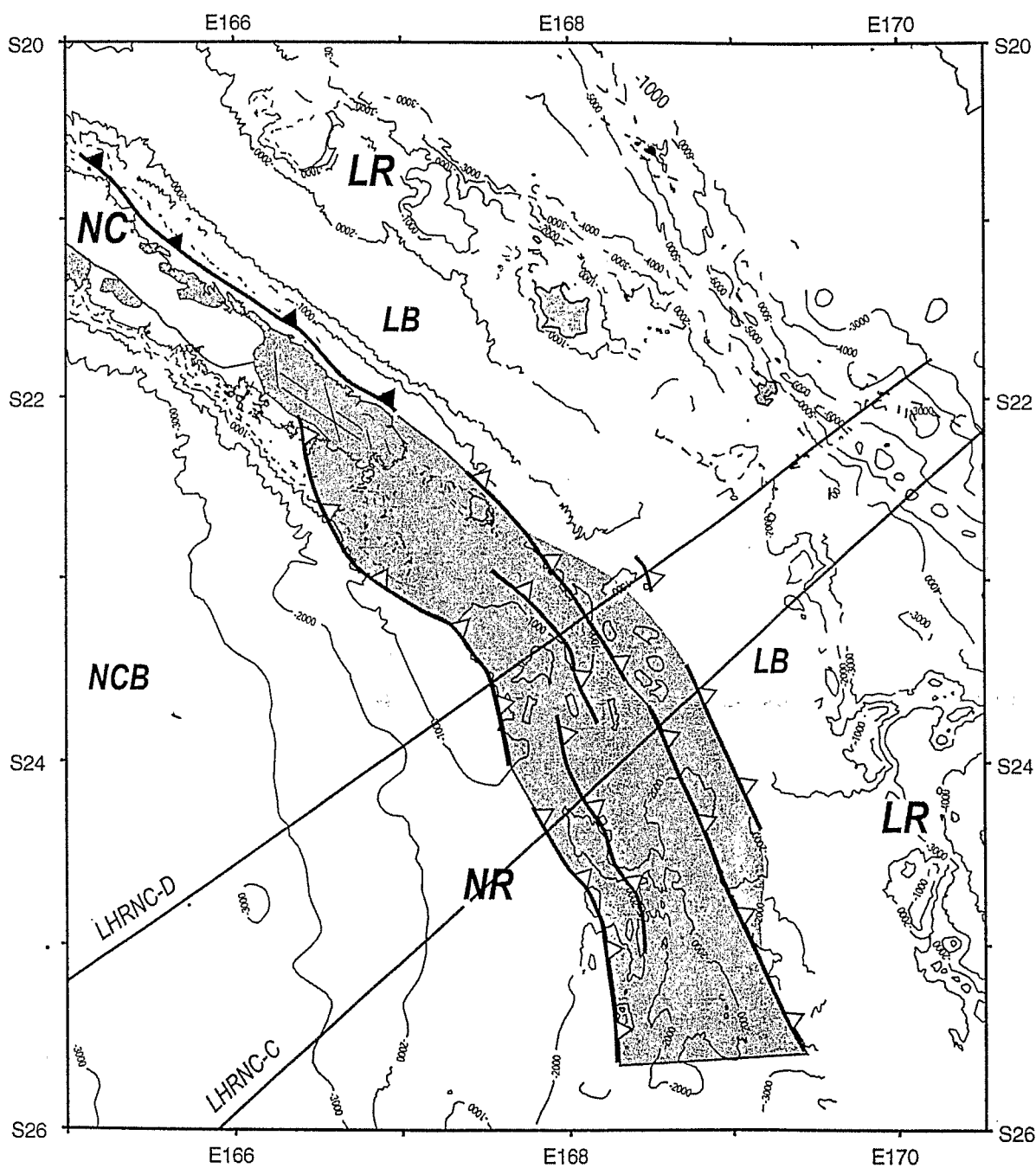


Fig. 7. Structural sketch showing the connection between offshore and onshore structures. The limits of the New Caledonian ophiolites are defined from Paris (1981) on New Caledonia and Cabioch et al. (1995) in the southern Caledonian reef area.

Acknowledgements

FAUST Project is a joint project funded by IFREMER and AGSO. We thank all the participants on the FAUST 1 *Rig-Seismic* cruise for the acquisition and the preliminary processing of the seismic data. We also thank Ray Wood and an anonymous referee for their very useful review of a first draft of the manuscript.

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